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Lewis Research Center
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SUMMARY

Time variations in combustion parameters are measured in a zone of oscillatory combustion to aid in formulating a model of the oscillatory-combustion process. The study centers on a single 0.028-inch-diameter liquid-oxygen jet reacting with diffusely injected gaseous hydrogen in a two-dimensional circular combustor. Instability is coupled with the first spinning transverse mode.

A correlation of pressure and gas velocity shows a predominantly in-phase relation approaching that of a plane traveling wave. Gas velocities agree with calculated values for an isentropic wave process using experimentally determined gas properties.

Photographs of the liquid jet correlated with phase position in the wave show the response of the jet to its changing environment. Mass removal from the jet is continuous but varies with time and is in the form of unresolved small drops or vapor. It appears to lag behind the pressure and velocity change. Mean jet length agrees with that predicted for steady transverse gas velocities.

Radiation surveys indicate energy release at and beyond the position of mass release from the jet. The distributed radiation pattern may be attributed to gas-phase mixing processes. Time variations in gas radiation are basically in phase with pressure and primarily correspond to an isentropic process for a gas composition in thermodynamic equilibrium. Cyclic reaction beyond this in-phase and concentration-dependent behavior is indicated by a skewing of the radiation wave shape in the direction of increasing time. A portion of the energy released appears to lag behind the pressure change.

A conceptual model of instability based on the observed parameter variation is presented. Energy addition to the wave is dependent on the mass released from the jet, gas mixing, and a concentration-dependent reaction process. The effect of mass release is amplified by a steady gas flow.

INTRODUCTION

An ultimate goal in combustion research is to describe analytically and to interrelate the various processes encompassing the combustion phenomena. In steady combustion, such descriptions are frequently time or space functions in which time and space are in themselves related. In oscillatory combustion, time and space parameters may vary independently, and analytical relations not only become more complex but may vary substantially from those for steady combustion.

Transient and oscillatory combustion processes have been studied by various investigators. Shock-tube experiments provide a large source of such data. Studies of the combustion process (refs. 1 and 2), of chemical kinetics (refs. 3 and 4), and of the separate process of atomization (refs. 5 to 7) are examples of shock-tube applications. Analytical-model studies (refs. 8 to 10), although conducted to obtain stability criteria, indicate the parameter variations to be expected from an interaction of processes. The complete combustion system has also been used to study the interaction of processes (refs. 11 to 13). Such an experimental approach is used in this investigation.

The purpose of this study is to inquire into the time variations of combustion parameters at various positions in a zone of oscillatory combustion, to examine these parameters for deviations from steady processes, and to formulate a model for oscillatory combustion. The mass and energy release processes are examined in particular because they provide the driving force for sustained oscillations.

The investigation is made in a two-dimensional circular combustor with radial flow of propellants and combustion gases. An isolated 1-inch-diameter combustion zone centered on a 0.028-inch-diameter oxygen jet reacting with hydrogen is observed macroscopically for mass and energy release processes during instability. The acoustic environment is that of traveling transverse oscillations. A single condition of instability is studied. The oscillatory pressure ratio is 1.91 at a frequency of 4350 cps for the first spinning transverse mode.

SYMBOLS

A_n	nitrogen orifice area
a	speed of sound
C_1, C_2	constants
c_p	specific heat at constant pressure
D_o	oxygen orifice diameter
f	frequency
g	gravitational constant

L_b	jet breakup length
L_i	initial jet breakup length
P_c	combustor pressure
$P_{n,t}$	nitrogen orifice throat pressure
R	specific gas constant
r	radius
T	gas temperature
u_c	combustion gas velocity
u_ℓ	liquid velocity
u_n	nitrogen gas velocity
$\overline{u}_\theta$	mean tangential velocity
W	wave velocity
w_c	combustion gas weight flow rate
w_n	nitrogen gas weight flow rate
γ	ratio of specific heats
ρ_g	gas density
ρ_ℓ	liquid density

COMBUSTOR CHARACTERISTICS

The experimental data were obtained from the two-dimensional circular combustor shown in figure 1. Operating characteristics of this combustor are described in reference 14. The combustor cavity is 8 inches in diameter and 1/2 inch in length, and propellants and combustion gases flow radially from the circumference to an exhaust nozzle in the center of one cover plate. The injector consists of 48 radially alined oxygen orifices and indirect passages for gaseous hydrogen. Although the configuration differs from usual combustor designs, the orientation between wave motion and propellant flow simulates axial-flow-combustor characteristics.

Figure 2 shows the details of the injector manifolding. Oxygen orifices are 0.028 inch in diameter and have a length-diameter ratio of 6.5. Hydrogen is introduced through slots located on both sides of the oxygen orifice. The hydrogen path is indirect and spreads and diffuses upon entry into the cavity. The hydrogen slots occur only at the angular position of alternate oxygen orifices. This deviation from complete

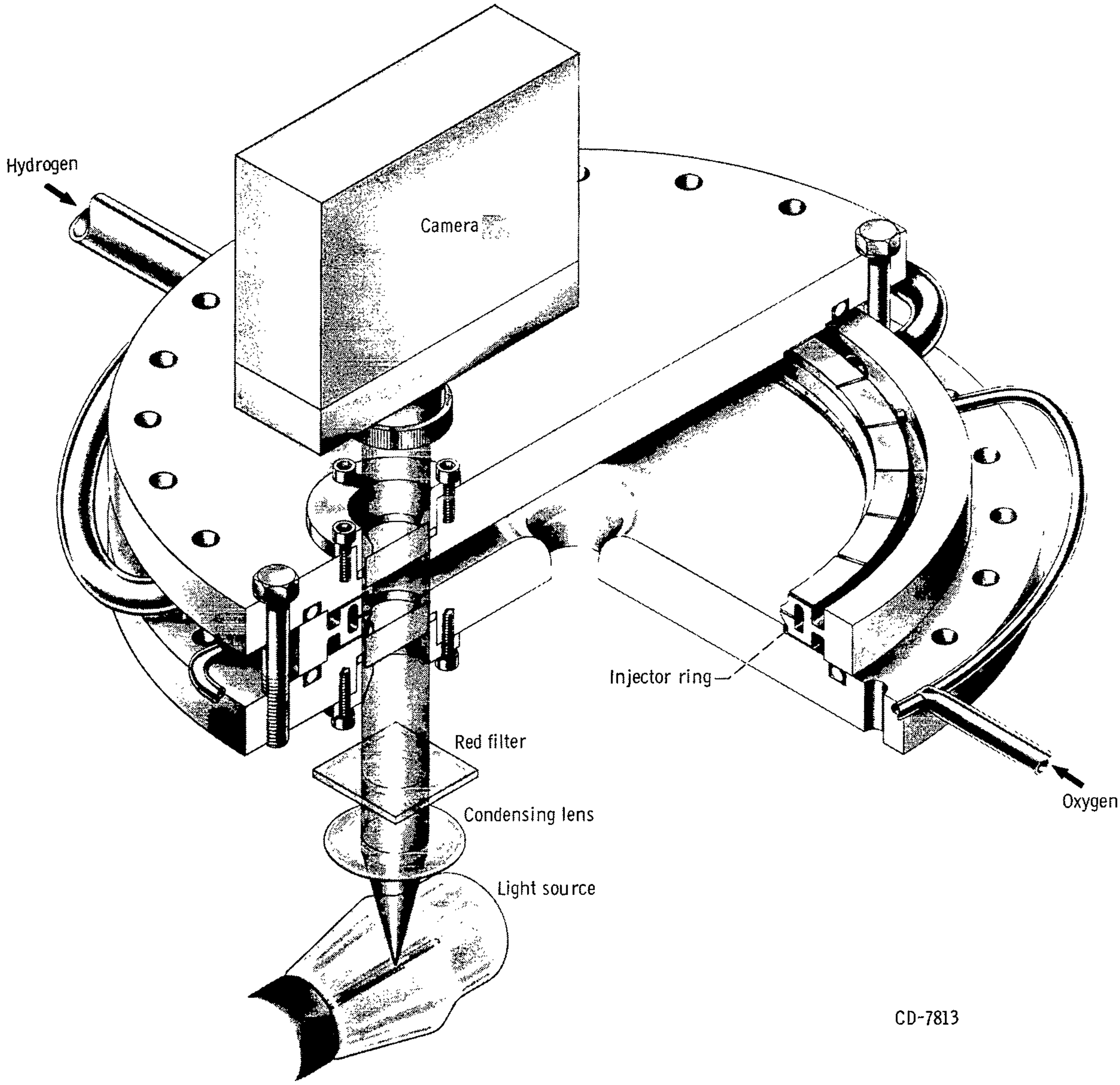


Figure 1. - Two dimensional circular combustor and photographic arrangement.

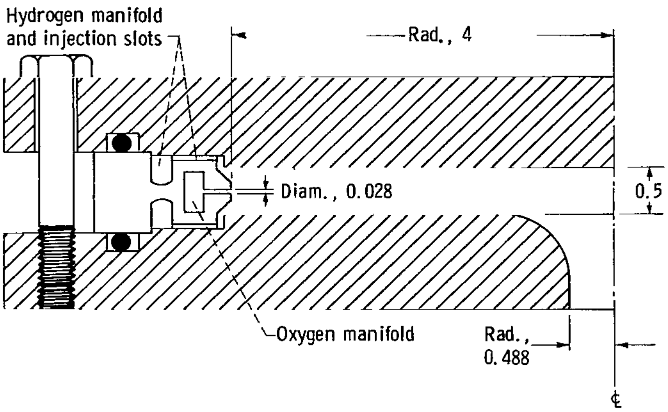


Figure 2. - Injector configuration. (Dimensions in inches.)

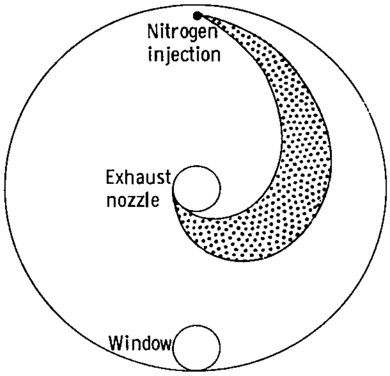


Figure 3. - Mean path of nitrogen flow.

symmetry resulted from development changes that were terminated when an unstable combustion device was obtained. Observations were made through the window ports shown in figure 1. The region of observation is a 1-inch-diameter circle including an oxygen orifice and a hydrogen injection slot. Fused quartz windows recessed 1/16 inch from the wall were used.

A circular flow of combustion gases was induced by tangential injection of a steady flow of nitrogen gas. This circular flow was required to establish a self-sustained spinning transverse mode of oscillation. Nitrogen gas was injected diametrically opposite the window port and did not enter the field of view because of combined radial and circular flow, as can be seen in figure 3. Normal test firings were 1.5 seconds in duration with nitrogen injected after 1 second of steady burning. The instability was programed for about 0.3 second.

Combustion parameters at a single operating condition are investigated. The condition is a mean chamber pressure of 260 pounds per square inch absolute, a metered oxygen-hydrogen weight flow ratio of 4.5, a total propellant flow rate of 0.7 pound per second, and a nitrogen flow rate of 0.22 pound per second. This condition is in an instability region where pressure ratios of about 2 occurred at a frequency of about 4400 cps.

MEASUREMENT TECHNIQUES

Combustion parameters during instability were obtained by the use of the following experimental techniques.

Chamber Pressure

A crystal-type transducer was used to indicate chamber pressure. The transducer in a water-cooled mounting is shown in figure 4. It was located 1/2 inch from the circumference - the same radial distance from the exhaust nozzle as the midpoint of the window port. The pressure signal was displayed on a cathode-ray oscilloscope and photographed. The dynamic-pressure instrumentation was supplemented by that used for performance evaluation.

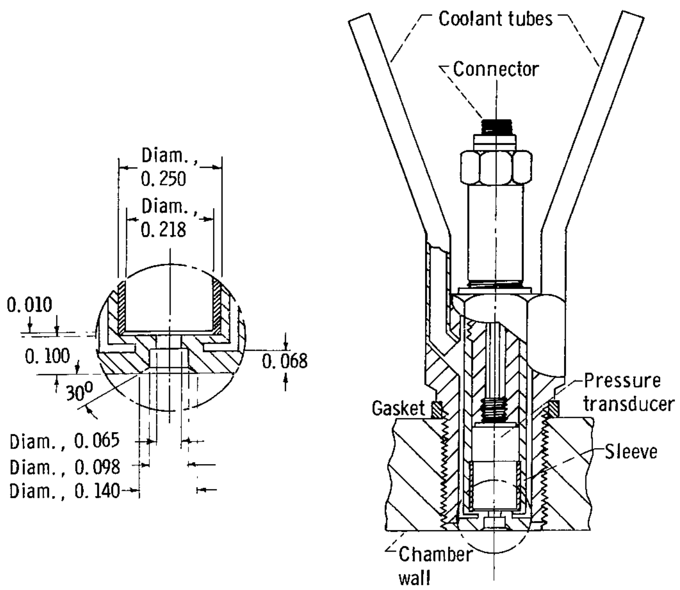


Figure 4. - Details of high-frequency pressure transducer. (Dimensions in inches.)

High-Speed Motion Pictures

Combined silhouette and self-luminous photographs were taken of the liquid-oxygen jet with a high-speed motion-picture camera. Figure 1 shows the optical arrangement. Light from a concentrated zirconium-arc lamp was passed through a filter so that visible wavelengths longer than 5800 angstroms were transmitted through the combustor. The silhouette of the oxygen jet formed by this red light was photographed on high-speed color film balanced for 3200^{0} K light; hence, only the red emulsion of the tricolor film was used for this image. The characteristic radiation of hydrogen-oxygen combustion is reported in reference 15 to be concentrated at short wavelengths. The spectral distribution and film sensitivity were such that combustion radiation predominantly exposed the blue emulsion of the film. The green emulsion was not used. The superpositions of transmitted- and combustion-luminosity photographs on the same film were examined separately by the proper selection of filters. Oxygen-jet characteristics and the combustion zone surrounding the jet were obtained from such films.

In the photography of oscillatory combustion the camera framing rate was adjusted to a value near the oscillatory frequency. This gave a stroboscopic effect in which successive pictures were taken at small but progressively changing phase positions in the pressure cycle. Exposure time for each photograph was about one-tenth of the wave period.

Streak Photographs

Streak photographs were taken for displacement, velocity, and luminosity data.

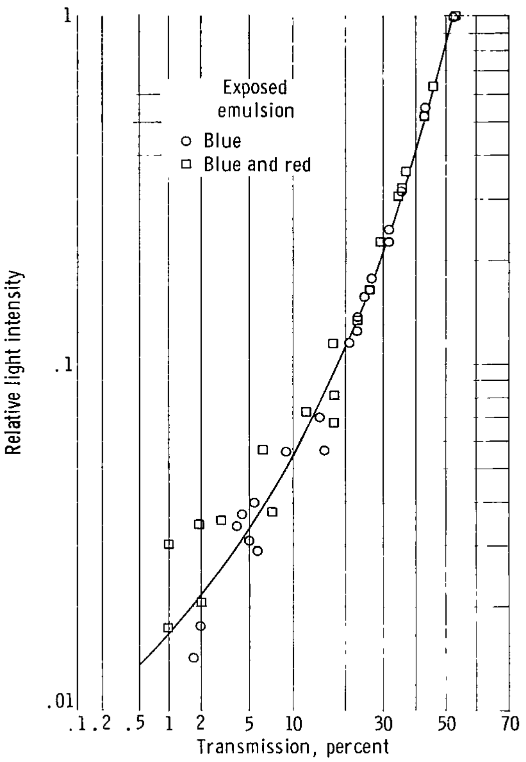


Figure 5. - Blue-emulsion calibration of color film.

The photographic arrangement was similar to that for motion-picture photography (fig. 1). Transmitted and emitted combustion light was recorded on color film with a motion-picture camera. Displacement data were recorded as viewed through a 1/32-inch-wide slit aperture located on the combustion side of the window. Slit and camera orientation were adjusted to indicate time variations along either radial or tangential paths.

Time displacement was displayed on the film of both the heterogeneously luminous combustion gases and the silhouetted oxygen jet. Streaks produced by the combustion gases were used for gas velocity indications in the vector direction of the slit orientation. Absolute evaluation of velocity, however, may not be precise because of the limitations in continuous tracking and identification of the gas zone. Streaks of the silhouetted oxygen jet provided additional information on jet behavior during instability.

Approximate radiation intensities were also obtained from the streak photographs. Film transmission densities for blue light were obtained from recording densitometer measurements. Time variations in transmission densities at a specific position were obtained. Density measurements were converted to relative radiation intensity from a calibration of the film. The calibration curve obtained by time and aperture changes of exposure is shown in figure 5.

Time Correlation

Transducer signals were time correlated by being simultaneously displayed on an oscilloscope screen. Chopper amplifier techniques for multibeam display were used. A high-intensity lamp with 1-microsecond light pulses at 0.01-second intervals provided a signal for time correlation of oscilloscope signals with combustion photographs. The light was directly photographed on the combustion film records and indicated on the oscilloscope with a photoelectric circuit. Measurements taken at different positions in the combustor were time adjusted from a knowledge of the wave propagation velocity.

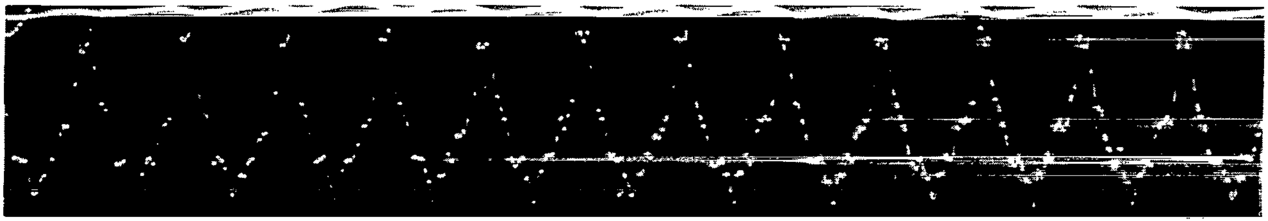


Figure 6. - Oscilloscope record of combustor pressure.

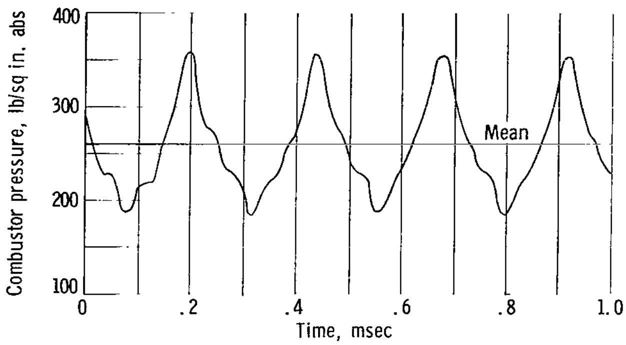


Figure 7. - Reduced combustor pressure 1/2 inch from circumference. Frequency, 4350 cps.

RESULTS AND DISCUSSION

Chamber Pressure

An oscilloscope record of the chamber-pressure oscillation is shown in figure 6. The oscillation in pressure is typical of that experienced for all runs; however, a detailed makeup of the waveform was not completely reproducible. Higher harmonic components were always evident; they were caused by either pickup ringing or higher modes of oscillation within the combustor. Electronic filtering was not used because of the indefinite phase shift caused by such techniques.

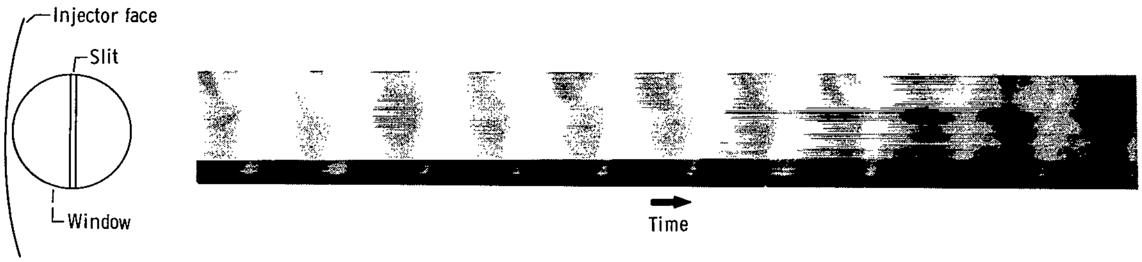
The chopper amplifier used in the indicating circuit gave a 26-point resolution per cycle. Figure 7 shows the wave shape after numerical smoothing of these data points. A maximum pressure of 357 pounds per square inch absolute and a minimum pressure of 187 pounds per square inch absolute are indicated; these values give a pressure ratio of 1.91 and an amplitude that is 0.654 that of chamber pressure. The wave shape has the characteristics of the pronounced symmetrical spike attributed to strong spinning transverse waves in reference 16.

Chamber-pressure oscillations were measured at a combustor radius of $3\frac{1}{2}$ inches, whereas photographic observations were made at radial positions of 3 to 4 inches. The oscillatory pressure amplitude is theoretically related to radius by a first-order Bessel function. A variation in amplitude of only 7 percent is predicted for the window port area. This agrees with the experimental measurements of reference 17.

The measured oscillatory frequency in chamber pressure is 4350 cps. An expression for the frequency of the first spinning transverse mode (ref. 18) is

$$f = 0.293 \frac{a}{r}$$

A theoretical speed of sound of 4980 feet per second has been calculated for equilibrium combustion products for a mixture ratio of 4.5 with nitrogen dilution. Since the wave velocity is added to any bulk motion of the gases, a correction for circular



(a) Tangentially alined slit.

(b) Radially alined slit.

Figure 8. - Typical streak photographs of oscillatory combustion.

velocity produced by tangentially injected nitrogen must be made. Experimental measurements to be presented in the section Gas Velocity indicated this velocity be be 235 feet per second at the center of the window port. Corrections for this velocity give a predicted theoretical frequency of 4577 cps or an experimentally indicated speed of sound of 4720 feet per second. The indicated speed of sound is lower than theoretical. Incomplete combustion near the circumference, heat-transfer losses, and the effect of strong oscillations (ref. 16) could account for the difference.

Gas Velocity

Gas velocity determinations were made at the midpoint of the window 1/2 inch from the injector. Typical streak photographs for both tangentially and radially alined slits are shown in figure 8, and the indicated velocities are presented in figure 9. Both the tangential and radial velocity indications are shown correlated with time and pressure. The general characteristic shown is that of a spinning transverse mode. The tangential component is in phase with pressure, and the radial component is 90° out of phase. The accuracy of the velocity determinations from the streak photographs is variable. With the original films the accuracy for peak velocities is estimated to be within 5 percent. A greater inaccuracy occurs at lower velocities and when simultaneous tangential and radial displacements obscure the record.

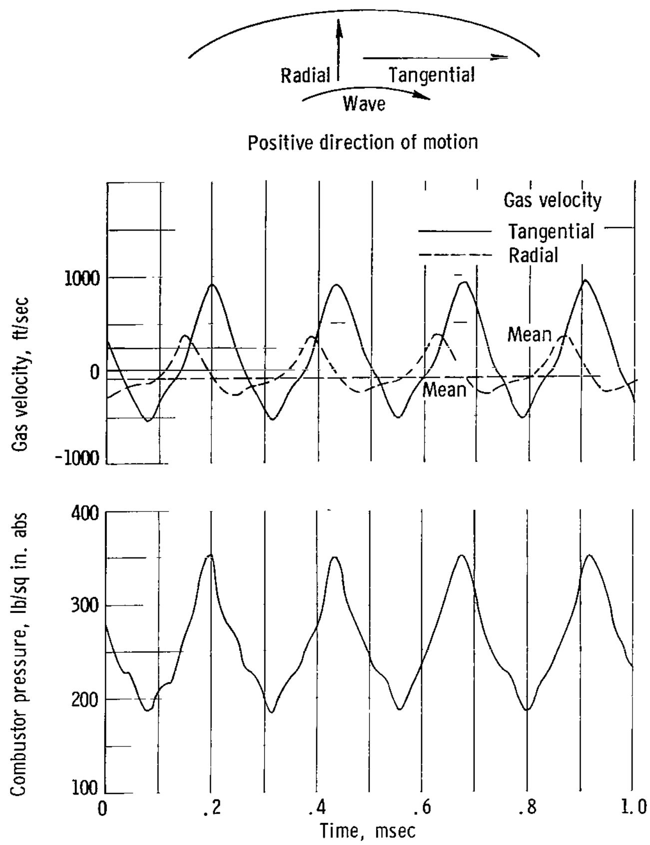


Figure 9. - Indicated gas velocity 1/2 inch from injector correlated with chamber pressure.

The tangential velocity is basically symmetrical about a mean value of 235 feet per second with oscillations of about ±750 feet per second. This mean value or constant tangential velocity is attributed to the circular flow induced by tangentially injected nitrogen. It is a specific property of this test and not a general characteristic of the spinning mode.

The circular flow induced by tangentially injected nitrogen can be theoretically approximated from a momentum balance:

$$\bar{u}_\theta(w_c + w_n) = w_n u_n + (P_{n,t} - P_c) A_n g \qquad (1)$$

The nitrogen was injected from a 1000-pound-per-square-inch-absolute source with critical flow through a 1/8-inch-diameter orifice. These values, together with a propellant flow of 0.7 pound per second, a nitrogen flow of 0.22 pound per second, and a combustor pressure of 260 pounds per square inch absolute can be used to compute a circular flow. A velocity of 394 feet per second is required to balance the momentum equation. The measured value of 235 feet per second is only 60 percent of this value. The loss of momentum is attributed to wall impingement, jet expansion angle, turbulence, and friction losses. Acoustic streaming, a circular flow accompanying a strong wave that rotates opposite to the wave (refs. 16 and 19), would also reduce the experimentally observed value.

The radial velocity is similarly biased by a mean gas flow. In this case it is caused by the flow of combustion products toward the nozzle. A value of 95 feet per second was determined from the mean slope of the particle streaks. The instantaneous values of radial velocities are questionable because of indistinct streaks. Maximum values of 380 feet per second in the direction of the circumference and 280 feet per second in the direction of the nozzle were indicated. The mean radial velocity of 95 feet per second and the indicated speed of sound of 4720 feet per second are best satisfied by a model in which combustion is limited by oxygen vaporization, as in that of reference 20. They agree with a condition where, 1/2 inch from the circumference, more than 50 percent of the oxygen remained to be burned.

In a vector sum of the velocities shown in figure 9, the contribution of the radial component is relatively small. The wave has the predominant characteristics of a plane traveling wave at the position of measurement with velocity variations similar to the tangential component. This agrees with analytical treatments (refs. 16 and 18) where plane wave characteristics exist at the circumference and deviate substantially from this condition only on approaching the center of the cavity.

The oscillation in velocity is related to the pressure oscillation from acoustic theory. An approximation of this relation can be obtained by assuming the wave to be plane and one-dimensional at a point near the circumference of the cavity. For such a wave, the energy of a gas particle with respect to the wave is

$$\frac{(u_c - W)^2}{2} + c_p T = C_1 \tag{2}$$

If small-perturbation theory applies, the relation becomes

$$(W - u_c)\Delta u_c = c_p \ \Delta T \tag{3}$$

For an isentropic process such that

$$T = C_2 P_c^{(\gamma-1)/\gamma}$$

$$c_p = \frac{\gamma}{\gamma - 1} gR$$

$$a^2 = \gamma g R T$$

a relation between particle velocity and pressure can be formulated:

$$(W - u_c)\ \Delta u_c = \frac{a^2}{\gamma} \frac{\Delta P_c}{P_c} \tag{5}$$

The wave velocity W as approximated by the frequency of the oscillation is $W = 2\pi rf - \bar{u}_\theta$ and $W - u_c \cong W$. The perturbation in particle velocity is then related to combustor parameters by the relation

$$\Delta u_c = \frac{a^2}{\gamma(2\pi rf - u_\theta)} \frac{\Delta P_c}{P_c} \qquad (6)$$

The experimentally determined values of these parameters as previously presented are $a = 4720$ feet per second, $f = 4350$ cps, and $\bar{u}_\theta = 235$ feet per second. For an average γ of 1.2, the velocity-pressure relation at the radius of the window port is

$$\Delta u_c = 2410 \frac{\Delta P_c}{P_c}$$

For a pressure amplitude $\Delta P_c/P_c$ of 0.654 the velocity perturbation Δu_c is 1570 feet per second or ±785 feet per second about a mean value. The agreement between the experimental value of ±750 feet per second and the value computed for indicated gas properties is relatively good. The wave appears to have isentropic properties.

Oxygen-Jet Characteristics

A sequence of high-speed motion pictures of the liquid jet taken from the 1-inch-diameter window is shown in figure 10. The relative phase position with respect to the pressure oscillation and the approximate magnitude and direction of the velocity vector are shown below each photograph. These pictures were taken in successive cycles of the oscillation at a repetition rate that is slightly less than the period of one cycle.

Figure 10 and other film sequences show cyclic displacement and distortion of the liquid jet. The characteristics observed are the cumulative effect of time-varying forces caused by the velocity and pressure changes shown in figure 10. In the vicinity of the orifice, the jet direction approximates that of the velocity vector. At the extremity of the jet, a correlation becomes difficult because jet displacement and distortion are the cumulative effects of forces over a time interval. This time interval computed from jet velocity measurements is about two cycles of oscillation.

The resolution of these photographs is not sufficient in detail to show the mass removal process. Mass removal appears continuous but varies with time in magnitude and direction; it is in the form of unresolved vapor or small drops that quickly lose their identity.

These jet characteristics are a pronounced change from an equivalent stable operating condition (ref. 14). During stable combustion, the jet length extends beyond the 1-inch window. The oscillations reduce the length to about 1/4 inch, as shown in figure 10. A combustion length of 1/4 inch implies a chemical conversion rate of the order of 0.1 pound per second per cubic inch or 500 Btu per second per cubic inch. These

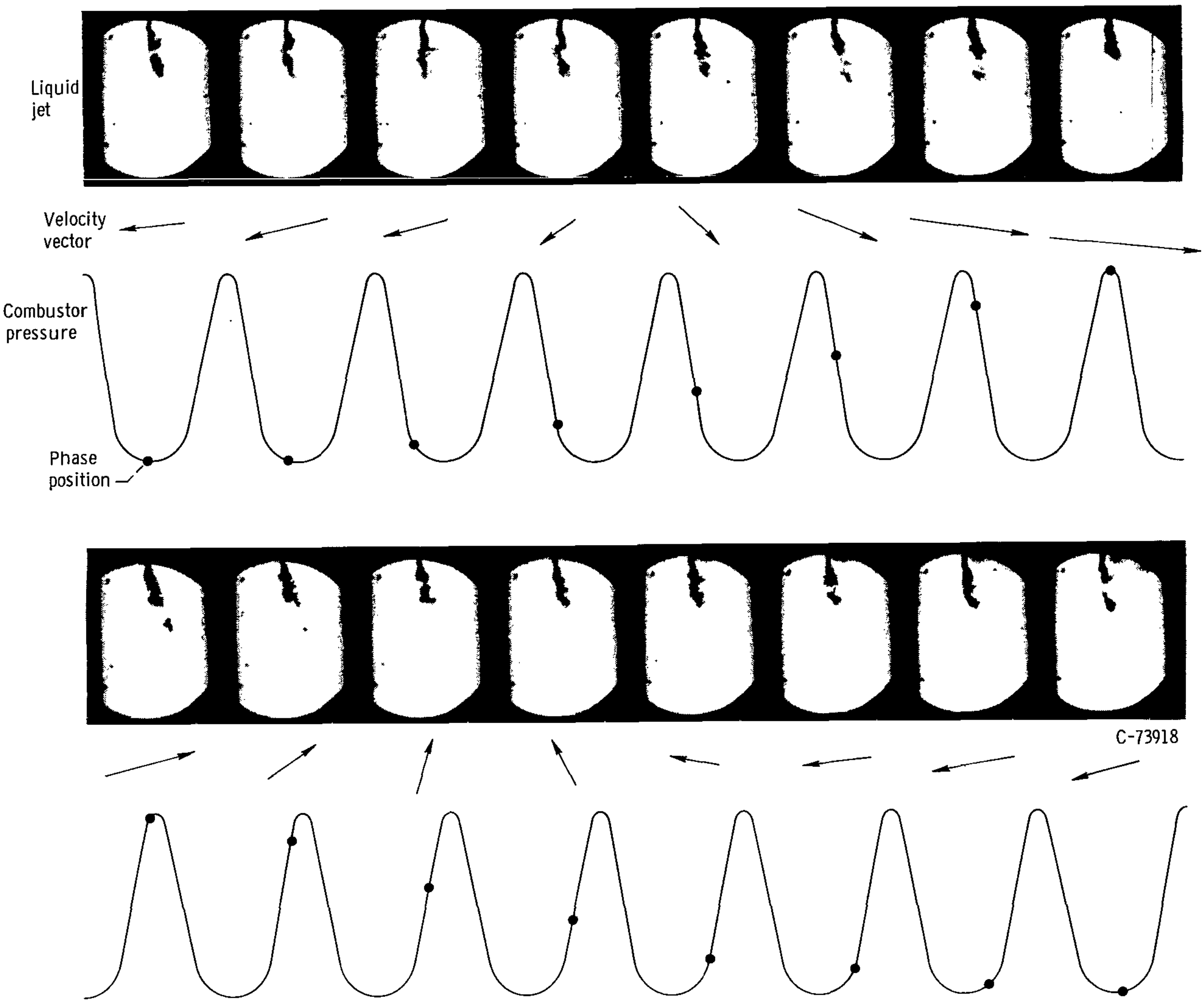
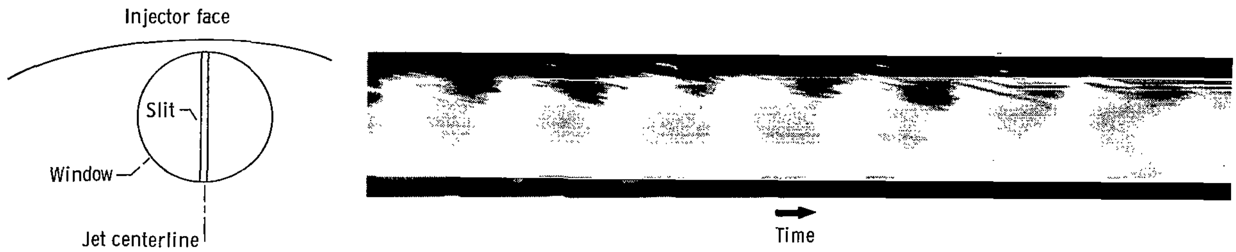


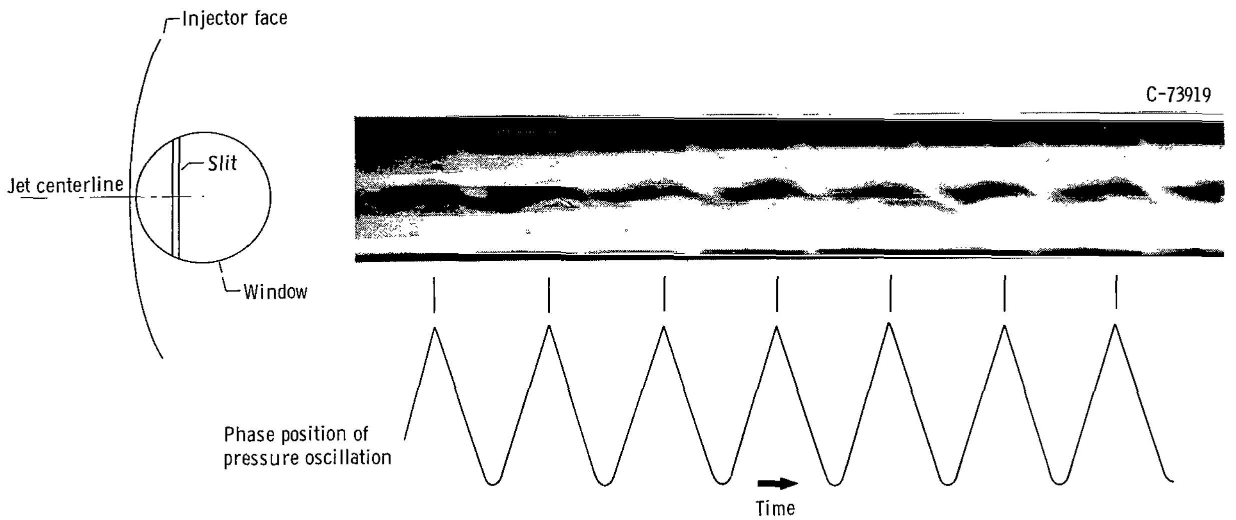
Figure 10. - Velocity vector and phase position for sequence of jet photographs.

values are comparable with those for large-scale combustors of efficient design. The instability of this model combustor is comparable with the instability of full-scale combustors in its energy release environment, even though other design parameters may differ significantly.

Figure 11 shows streak photographs of the silhouetted oxygen jet by means of radial and tangential camera slit alinements. Liquid displacement along a radial path that includes the orifice is shown in figure 11(a). The average partial slope along a radial path indicates a jet velocity of 30 feet per second. No significant oscillation in slope is apparent. Injection velocity apparently is not affected by the varying pressure drop across the orifice. A change in the density of oxygen streaks is evident. Such changes are probably caused by lateral displacement of the jet during instability.



(a) Radial slit alinement.



(b) Tangential slit alinement 1/4 inch from injector.

Figure 11. - Streak photographs of liquid jet in silhouette.

Streak photographs with a tangentially alined slit (fig. 11(b)) were taken 1/4 inch from the orifice. An abrupt periodic change in jet cross section is evident at this position. A correlation with the phase position of the peak combustor pressure (fig. 11(b)) shows the jet disappearance to lag behind the pressure peak by 10 milliseconds or more. This time lag is significant only for the position of measurement and would differ for other positions along the jet length. A study of the high-speed motion pictures indicates that the position of cross-sectional change along the jet varies during a cycle of oscillation. At the jet extremity, the cross section is continually distorted, whereas no distortion occurs at the orifice. Jet breakup as a whole is therefore continuous but time varying and becomes abrupt only with respect to specific positions near the orifice.

If mass removal or jet breakup is the integral effect of an applied force, the mass removal would be expected to lag behind the oscillations in force. Such delays have been studied in shock tubes (refs. 5 and 6) for a step change in force. Complete breakup can occur in about 1 millisecond, although the process begins at much shorter times.

For the oscillating flow field of this study, the force reverses direction in less time than the period for complete breakup. Additional information on the dynamic response of the jet would be needed to compare shock-tube results with this study.

Breakup of a liquid jet with a steady transverse flow of gas was studied in the investigation of reference 21. The distance for the initiation of breakup L_i and the distance for complete breakup L_b were found to be approximated by the relations

$$L_i = D_o \frac{u_\ell}{u_c} \sqrt{1.5 \frac{\rho_\ell}{\rho_g}}$$

and

$$L_b = D_o \frac{u_\ell}{u_c} \sqrt{12.5 \frac{\rho_\ell}{\rho_g}}$$

These correlating parameters were derived for nonvarying flow conditions. Applying them to this study gives relatively good agreement when integrated mean values of cross velocity and gas density are used. If $D_o = 0.028$ inch, $\rho_\ell = 75$ pounds per cubic foot, $\rho_g = 0.1$ pound per cubic foot, $u_\ell = 360$ inches per second, and $u_c = 4000$ inches per second, an initial breakup distance of 0.075 inch and a complete breakup distance of 0.22 inch will result. Jet appearance in figure 10 generally agrees with such lengths.

Oscillations in jet breakup length are expected during instability, and the streak photographs (fig. 11) indicate they exist. The oscillation in jet length is not obvious in the jet photographs of figure 10; however, an extreme condition can be estimated. If the jet is assumed to be completely shattered by only the positive velocity peak, the jet can grow no longer than the jet travel distance in one cycle. In such an extreme case, jet breakup length would vary by less than 1/8 inch.

A detailed analytical description of the jet characteristics is not possible from this study. Jet displacement and distortion vary in both degree and direction, and a complex expression in time and space would be required to describe them analytically.

Gas Radiation

Gas radiation measured at the center of the window port is shown correlated with time and chamber pressure in figure 12. Radiation and pressure are basically in phase; however, the radiation waveform is skewed in the direction of increasing time with respect to the pressure waveform. This difference implies a degree of nonlinear behavior in the processes relating pressure and radiation.

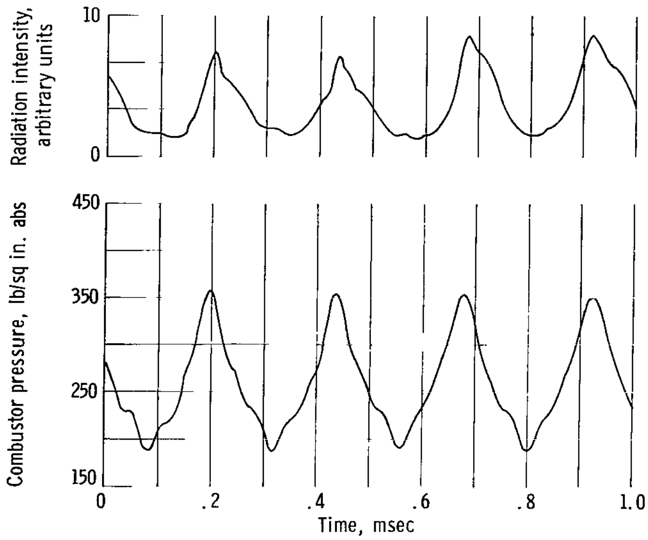


Figure 12. - Radiation intensity 1/2 inch from injector at jet centerline correlated with combustor pressure.

An interpretation of such radiation measurements is aided by the studies reported in references 15 and 22. In these studies the radiation from hydrogen and oxygen reactions in rocket combustors was studied spectrally under a variety of reacting conditions. The spectral distribution was attributed to line and band spectra of the hydroxyl radial (OH), molecular oxygen (O_2), and water vapor (H_2O) with a weak continuum, which remained proportional to OH radiation. Radiation intensity peaked in the region of stoichiometric mixture ratios and exceeded the radiation of the fuel-rich mixtures (oxygen-fuel ratios <4.0) by an order of magnitude. Radiation emitted by these reacting gases was found to be in local thermodynamic equilibrium. No evidence of chemiluminesence or radiation from intermediate species was noted. The radiation from reacting zones was considered the same as that from reaction products.

The blue-sensitive emulsion of the color film (ref. 23) used in this study was selectively exposed by the OH and O_2 radiation with an exposure primarily indicative of OH radiation. The most intensely exposed zones in a photograph of these heterogeneous gases are assumed to be gases at or near stoichiometric proportions. A correct exposure of such zones would give little or no exposure for end products at a mixture ratio of 4.5. For the short path length through the combustor, 5/8 inch, radiation is assumed proportional to concentration. On the basis of these considerations, the radiation measurements are assumed to be those of OH concentration in gases near stoichiometric proportions and an index of the mass of propellant undergoing reaction.

Radiation varied directly with pressure, as shown in figure 12. With radiation proportional to OH concentration, such a change would result from isothermal compression alone. An isentropic temperature change, however, should occur. The temperature change could affect the OH concentration in a unit volume of gas in thermodynamic equilibrium by changing equilibrium rates, as well as by changing gas density. Temperature can also affect radiation intensity according to Planck's law. When all these effects are included for a stoichiometric mixture of gases and the measured pressure oscillation, the computed curve shown in figure 13 is obtained. Relatively good agreement of the amplitudes of the measured and computed curves is shown. About 75 percent of the computed amplitude is due to the temperature effect in Planck's law and 25 percent to the change in OH concentration in a unit volume. Such behavior would be

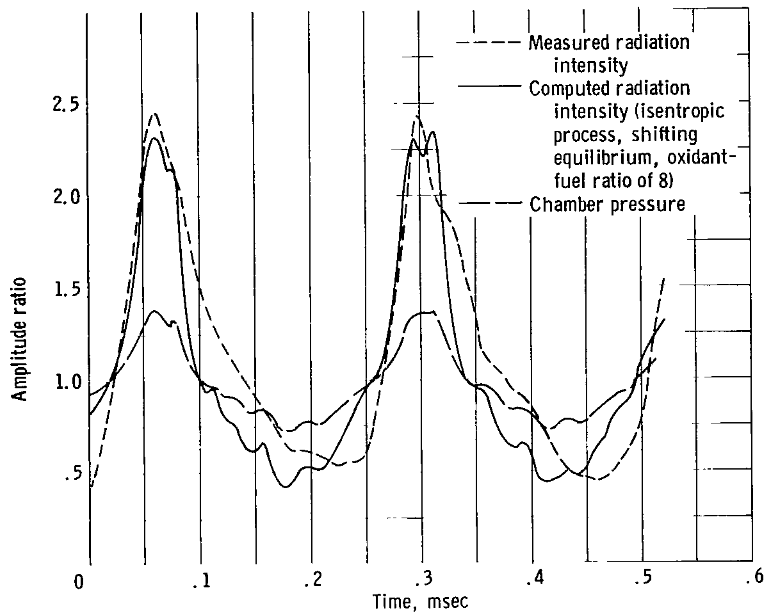


Figure 13. - Comparison of measured and computed radiation intensity.

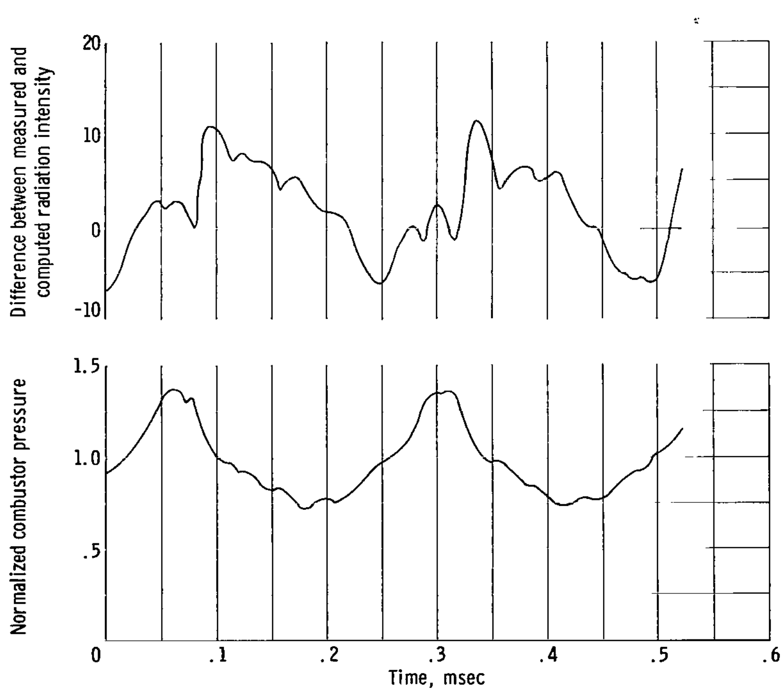


Figure 14. - Difference between measured and computed radiation intensity compared with pressure oscillation.

(a) On jet orifice centerline. (b) 1/2 Inch from injector.

Figure 15. - Variations in radiation intensity.

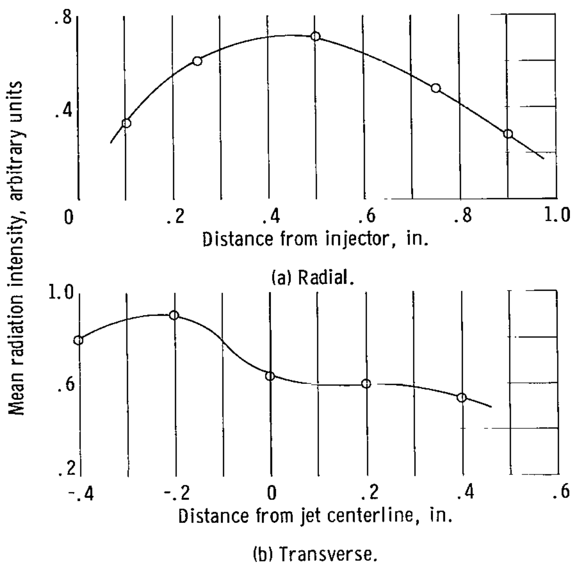


Figure 16. - Mean value at radiation intensity in transverse and radial direction through midpoint of window.

expected from a reaction process in a zone where the mole fraction of reactants remains constant.

The difference in the wave shape of the calculated and measured radiation may be used for additional examination of the combustion process. The differences in these two curves are shown in figure 14. A cyclic variation that lags behind the pressure oscillation by about 0.03 to 0.06 millisecond is obtained. This lag, if realistic, may reflect the lag observed in jet breakup or mass release.

Dissociation and recombination of OH may also affect radiation wave shape. The recombination rate of OH has been reported (ref. 3) as having the largest effect on the kinetics of hydrogen and oxygen reactions. The time constant for recombination is expected to be less than 0.005 millisecond for the conditions of these tests. Its effect would be small for an oscillating condition with a time period of about 0.2 millisecond. A small time constant may be reflected in a wave shape change for the nonsinusoidal pressure wave shapes encountered in these tests. Some of the wave distortion noted in the radiation may be caused by this effect. Radiation computed on the basis of frozen compositions or a large time constant would reduce the expected oscillation in radiation by about 25 percent. It is interesting to note that only in the intermediate conditions between equilibrium and frozen composition can a phase shift or wave distortion occur.

Radiation measurements taken at various positions along both tangential and radial paths through the midpoint of the window port are shown in figure 15. The oscillations are similar to those at the window midpoint. The wave shape is skewed to varying degrees, and the amplitude of the oscillation varies. Considerably more irregularities in wave shape occur away from the circumference and near the lateral boundaries of the window. This is typical of turbulent flames, where sporadic reaction defines the end of the reaction zone.

The mean value of radiation intensity may also be used to examine the reaction process. The mean values along the tangential and radial paths are shown in figure 16. A peak value is shown near the midpoint of the window. If the level of radiation is assumed to be an index of reaction or energy release, it can be compared with the position of mass release from the jet. The jet disappears about 1/4 inch from the orifice, and liquid is evident about 1/8 inch on both sides of the jet-orifice centerline. Energy release peaks 1/2 inch from the orifice along a radial path and extends beyond the jet boundaries in the tangential direction. Based on this interpretation, energy release is distributed beyond the region of mass release from the jet and tends to confirm the previous deduction that less than one-half the oxygen is burned at the midpoint of the window port.

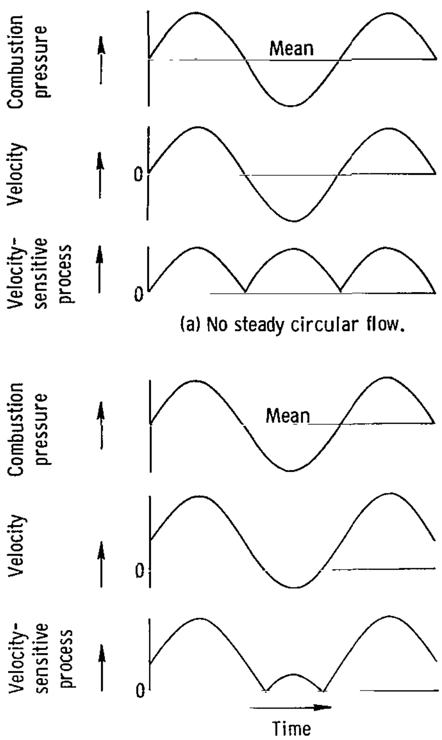
The evidence of radiation beyond the region where liquid oxygen is evident suggests that energy is released by mixing of fuel-rich and oxygen-rich gases. This mixing process is not readily defined from the measurements of this study. An attempt to interpret the radiation patterns showed that the simultaneous effect of mass transport, time variations in an identifiable zone, and heterogenity could not be individually resolved. It appears that such oscillatory data cannot be used directly but must be statistically averaged in some manner if a quantitative evaluation is to be made. This may be generalized to include most measurements made locally within the combustor because simultaneous time and space variations are inherent to the phenomena of instability.

Conceptual Model

A conceptual model of the unstable combustion process in the circular combustor can be formulated from the measurements and observations of this study. In this model, oscillatory conditions are assumed to be superimposed on a steady level of combustion in which liquid-oxygen jets are burning in an environment of gaseous hydrogen.

The history of liquid oxygen injected into an established state of instability is visualized as follows. A constant weight flow rate of oxygen enters an acoustic field associated with a spinning transverse mode of resonance. Gas velocity oscillations are in phase with pressure, as described by isentropic wave equations for mean values of gas properties. The entering oxygen jet is bent by the oscillating aerodynamic forces imposed on it. The rate and degree of bending depends on the applied force and the inertia of the liquid, which causes jet displacement to lag the oscillation in force.

The applied force on the jet also causes a distortion in jet cross-sectional area. This distortion grows with time and depends on the magnitude rather than the direction of the applied force. A limiting condition of distortion is obtained after some time interval, which is described as jet breakup. Jet length at breakup corresponds to the distance traveled by an element of liquid oxygen along the jet axis in this time interval. In the process of breakup, mass is continually released or removed from the jet in the form of vapor and small drops. The amount of mass released varies with time because of the time-varying cross-sectional distortion accumulated within the jet. This is a linear process when jet length variations are small; however, a phase displacement with the velocity oscillation may be expected.



(b) Steady circular flow.

Figure 17. - Conceptual effect of steady circular flow on velocity-sensitive process.

Vapor and small drops released from the jet undergo nearly instantaneous chemical conversion consistent with the local mixture ratio. The instantaneous mass flow rate of hydrogen-rich gases, which generate the force for the mass release rate of oxygen, determines this local mixture ratio. The ratio is approximately constant (ref. 7), although oxygen rich. Energy release, therefore, is only a fraction of that potentially available from the mass released from the oxygen jet.

Energy release in this case is controlled by a velocity-sensitive process that is relatively insensitive to the directions of the velocity vector. Such a process reaches a peak output twice during each pressure cycle (see fig. 17(a)). In-phase energy addition to the wave tends to be cancelled by out-of-phase energy addition. A steady circular gas flow was established in this study by tangential injection of nitrogen gas. Such a steady flow modifies conditions (see fig. 17(b)) by increasing the in-phase component at the expense of the out-of-phase component. The circular flow thereby amplifies the in-phase energy addition to the wave.

Only a portion of the energy released has been accounted for thus far. Energy continues to be released after some displacement from the position of mass release in the mixing of oxygen-rich and hydrogen-rich gases. The mixing is a turbulent diffusion process with combustion, flow, and instability establishing a mean intensity and scale of turbulence. It is a steady process in that, locally, the mole fraction of reacting gases is relatively constant. Energy release in a unit volume of gas, however, varies with the density oscillations accompanying the wave. Energy addition, therefore, is in phase with the pressure oscillations. The kinetics are those of concentration-controlled Arrhenius-type reactions.

The instability is sustained by the sum of the energy release controlled by mass release and mixing. The magnitude and phase of this energy addition to the wave balanced against the acoustic damping of the system establish a constant amplitude of pressure oscillations.

SUMMARY OF RESULTS

The measurement of oscillatory combustion parameters in a 1-inch-diameter zone near the circumference of a two-dimensional combustor gave the following results:

1. Pressure oscillations were those of strong spinning transverse oscillations at a frequency corresponding to the speed of sound for the mean gas properties.

2. Gas velocity oscillations were predominately in phase with pressure oscillations and were related by isentropic flow equations.

3. The liquid-oxygen jet was in a pseudostable condition with a continuous but time-varying removal of mass. Jet length agreed with calculated lengths for steady transverse flows.

4. Gas radiation was basically in phase with pressure and primarily agreed with that for an isentropic process in a gas in thermodynamic equilibrium. A skewing of the radiation wave shape in the direction of increasing time implied a lag in a portion of the energy released during a cycle.

5. Radiation surveys indicated that energy is released at and beyond the region of mass release from the liquid jet. The energy release pattern is attributed to gas mixing.

6. In a conceptual model, energy addition to the wave is dependent on the mass released from the jet and gas mixing with an amplified contribution of mass release caused by a steady gas flow.

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National Aeronautics and Space Administration,
Cleveland, Ohio, January 28, 1965.

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